Star Formation in the Milky Way and Nearby Galaxies

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Abstract

We review progress over the past decade in observations of large-scale star formation, with a focus on the interface between extragalactic and Galactic studies. Methods of measuring gas contents and star-formation rates are discussed, and updated prescriptions for calculating star-formation rates are provided. We review relations between star formation and gas on scales ranging from entire galaxies to individual molecular clouds.

Some definitions:

In general, we explicitly use "surface density" or "volume density," but for clarity, symbols with Σ refer to surface density, N refers to column density, and symbols with n or ρ refer to number or mass volume density, respectively. The surface density of HI gas is represented by Σ_{HI} if He is not included and by Σ(atomic) if He is included. The surface density of molecular gas is symbolized by Σ_{H_2}, which generally does not include He, or Σ_{mol}, which generally does include He. For

The conversion from CO intensity (usually in the $J = 1 \rightarrow 0$ rotational transition) to column density of H_2, not including He, is denoted X(CO), and the conversion from CO luminosity to mass, which usually includes the mass of He, is denoted α_{CO}.

The SFR is symbolized by SFR or $\dot{M}_*$, often with units of solar mass per year or solar mass per million years, and its meaning depends on how much averaging over time and space is involved. The surface density of SFR, (SFR), has the same averaging issues. The efficiency of star formation is symbolized by ε when it means $M_*/(M_* + M_{cloud})$, as it usually does in Galactic studies. For extragalactic studies, one usually means $\dot{M}_*/M_{gas}$, which we symbolize by ε'. The depletion time is indicated by $t_{dep} = 1/\varepsilon'$. Another time often used is the dynamical time, t_{dyn}, which can refer to the free-fall time (t_{ff}), the crossing time (t_{cross}), or the galaxy orbital time (t_{orb}). In recent years, it also has become common to compare galaxies in terms of their SFR per unit galaxy mass, or specific SFR (SSFR). The SSFR scales directly with the stellar birthrate parameter b, the ratio of the SFR today to the average past SFR over the age of the galaxy, and thus provides a useful means for characterizing the star-formation history of a galaxy.

The term starburst galaxy was introduced by Weedman et al. (1981), but nowadays the term is applied to a diverse array of galaxy populations. A common property of present-day populations of starbursts is an SFR out of equilibrium, much higher than the long-term average SFR of the system. No universally accepted quantitative definition exists, however. Some of the more commonly applied criteria are SFRs that cannot be sustained for longer than a small fraction (e.g., ≤10%) of the Hubble time, i.e., with gas-consumption timescales of less than 1 Gyr, or galaxies with disk-averaged SFR surface densities (SFR) $\geq 0.1\ M_{\odot}\ \mathrm{year}^{-1}\ \mathrm{kpc}^{-2}$ (Section 5.2). Throughout this review, we use the term quiescent star-forming galaxies to characterize the nonstarbursting galaxy population. Note that these local criteria for identifying starbursts are not particularly useful for high-redshift galaxies; a young galaxy forming stars at a constant SFR may resemble a present-day starburst galaxy more than a normal galaxy.

The recent influx of multiwavelength data has expanded the richness of information available on global star-formation properties of galaxies and transformed the interpretive framework from one based on morphological types to a quantitative foundation based on galaxy luminosities, masses, and other physical properties.

The role of galaxy mass as a fundamental determinant of the star-formation history of a galaxy has been long recognized (e.g., Gavazzi & Scodeggio 1996), but data from SDSS and subsequent surveys have reshaped our picture of the population of star-forming galaxies (e.g., Kauffmann et al. 2003; Baldry et al. 2004, 2006; Brinchmann et al. 2004). The integrated colors of galaxies, which are sensitive to their star-formation histories, show a strongly bimodal dependence on stellar mass, with a relatively tight “red sequence” populated by galaxies with little or no current star formation and a somewhat broader “blue sequence” or “blue cloud” of actively star-forming galaxies. The dominant population shifts from blue to red near a transition stellar mass of $\sim 3 \times 10^{10}\ M_{\odot}$ (Kauffmann et al. 2003). The relative dearth of galaxies in the “green valley” between the red and blue sequences suggests a deeper underlying physical bimodality in the galaxy population and a rapid evolution of galaxies from blue to red sequences.

A similar bimodality characterizes the mass dependence of the SFR per unit galaxy mass (SSFR). The mass dependence of the SSFR has been explored by numerous investigators (e.g., Brinchmann et al. 2004, Lee et al. 2007, Salim et al. 2007, Schiminovich et al. 2007). **Figure 8** shows an example from Schiminovich et al. (2007) using dust-corrected FUV measurements of SDSS galaxies.

A clear separation between the blue and red sequences is evident, and the dispersion of SSFRs within the blue sequence is surprisingly small, suggesting that some kind of self-regulation mechanism may be at work among the actively star-forming galaxies. The bimodality is not absolute; there is a clear tail of less active but significantly star-forming galaxies between the two sequences. These represent a combination of relatively inactive (usually early-type) disk galaxies and unusually active spheroid-dominated systems (Section 5.4). The sharp increase in the fraction of inactive galaxies above stellar masses of order a few $\times 10^{10}\ M_{\odot}$ is also seen.

The blue sequence in **Figure 8** is not horizontal; the SSFR clearly increases with decreasing galaxy mass. The slope (–0.36 for the data in **Figure 8**) varies somewhat between different studies, possibly reflecting the effects of different sampling biases. The negative slope implies that lower- mass galaxies are forming a relatively higher fraction of their stellar mass today and thus must have formed relatively fewer of their stars (compared with more massive galaxies) in the past. The most straightforward explanation is that the dominant star-forming galaxy population in the Universe has gradually migrated from more massive to less massive galaxies over cosmic time. Direct evidence for this "downsizing" is seen in observations of the SSFR versus mass relation in high-redshift galaxies (e.g., Noeske et al. 2007).

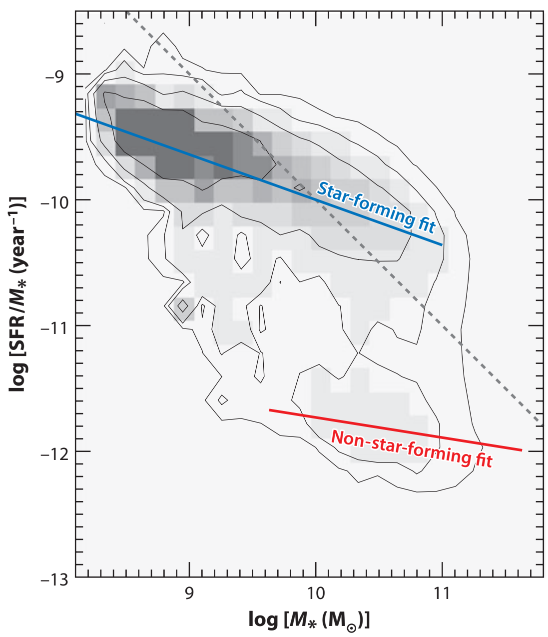

Figure 8

Relation between a specific star-formation rate (SFR) ($\dot{M}_*/M_*$) and galaxy mass for galaxies in the Sloan Digital Sky Survey (SDSS) spectroscopic sample and with SFRs measured from GALEX ultraviolet luminosities. Gray contours indicate the ($1/V_{max}$-weighted) number distribution of galaxies in this bivariate plane. The blue solid line shows the fit to the star-forming sequence, and the red line shows the approximate position of the non-star-forming red sequence on this diagram. The gray dotted line shows the locus of constant $SFR = 1\ M_\odot\ \text{year}^{-1}$. Figure adapted from Schiminovich et al. (2007); reproduced by permission of the AAS.

(Compare to inset in Galaxy MS below.)

Another instructive way to examine the statistical properties of star-forming galaxies is to compare absolute SFRs and SFRs normalized by mass or area. An example is shown in **Figure 9**, which plots integrated measurements of the SFR per unit area as a function of the absolute SFRs.

Several interesting trends can be seen in the data in **Figure 9**. For example, note the extraordinary range in SFRs, more than seven orders of magnitude, whether measured in absolute terms or normalized per unit area or (not shown) galaxy mass. Much of this range is contributed by nonequilibrium systems (starbursts). Normal galaxies occupy a relatively tight range of SFRs per unit area, reminiscent of the tightness of the blue sequence when expressed in terms of SSFRs. The total SFRs of the quiescent star-forming galaxies are also tightly bounded below a value of ~20 $M_{\odot}$ year^{-1} . Starburst galaxies as well as IR-luminous and ultraluminous systems, in particular, comprise most of the galaxies in the upper 2–3 decades of absolute SFRs and (SFR).

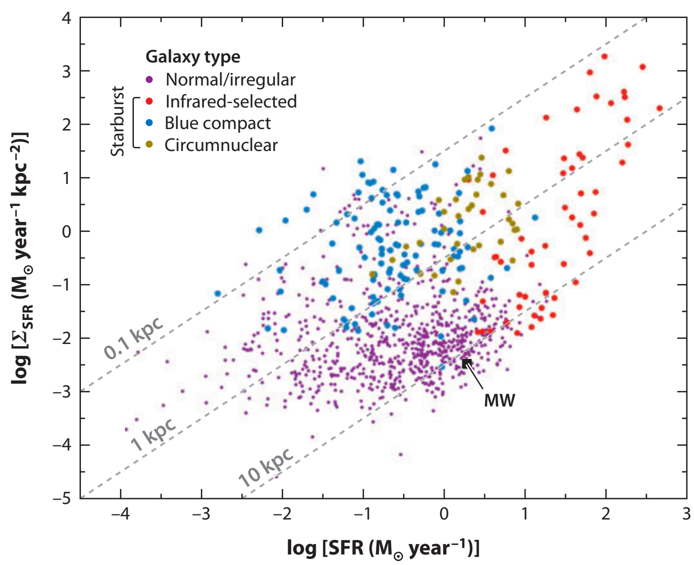

Figure 9

Distribution of integrated star-formation properties of galaxies in the local Universe. Each point represents an individual galaxy or starburst region, with the average star-formation rate (SFR) per unit area (SFR intensity) plotted as a function of the absolute SFR. The SFR intensities are averaged over the area of the main star-forming region rather than the photometric area of the disk. Diagonal gray lines show loci of constant star-formation radii, from 0.1 kpc (*top*) to 10 kpc (*bottom*). Several subpopulations of galaxies are shown: normal disk and irregular galaxies measured in Hα and corrected for dust attenuation (*solid purple points*) from the surveys of Gavazzi et al. (2003), James et al. (2004), Hameed & Devereux (2005), and Kennicutt et al. (2008); luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs, respectively) (*red points*) from Dopita et al. (2002) and Scoville et al. (2000); blue compact starburst galaxies measured in Hα (*blue points*) from Pérez-González et al. (2003) and Gil de Paz et al. (2005); and circumnuclear star-forming rings in local barred galaxies measured in Paα (*dark yellow points*) as compiled by Kormendy & Kennicutt (2004). The position of the Milky Way (*black square*) lies near the high end of normal spirals in total SFR, but it is near the average in Σ(SFR) (Section 5.1). The relative numbers of galaxies plotted does not reflect their relative space densities. In particular, the brightest starburst galaxies are extremely rare.

The distribution of SFRs along the X-axis of **Figure 9** (after correcting for volume completeness biases) is simply the SFR distribution function (e.g., Gallego et al. 1995, Martin et al. 2005b). **Figure 10** shows a recent determination of this distribution from Bothwell et al. (2011) based on flux-limited UV and TIR samples of galaxies and SFRs derived using the methods of Hao et al. (2011) and corrections for AGN contamination following Wu et al. (2010b, 2011). The SFR function is well fitted by a Schechter (1976) exponentially truncated power law, with a faint-end slope $\alpha = -1.5$ and characteristic SFR, SFR* = 9 $M_\odot$. Although SFRs as high as ~1,000 $M_\odot$ year^{-1} are found in present-day ULIRGs, the contribution of LIRGs and ULIRGs to the aggregate star formation today is small (<10%) (also see Goto et al. 2011). Steady-state star formation in galaxies dominates today. The value of SFR* increases rapidly with z, and galaxies with $L_{bol} > 10^{11}$ $L_\odot$ (i.e., LIRGs) become dominant by redshifts $z > 1$ (e.g., Le Floc'h et al. 2005). This change partly reflects an increase in merger-driven star formation at higher redshift, but at early epochs, even the steady-state star formation in massive galaxies attained levels of order tens to hundreds of solar masses per year, thus placing those galaxies in the LIRG and ULIRG regime. This suggests that most of the decrease in the cosmic SFR in recent epochs has been driven by downsizing in the level of steady-state star formation (e.g., Bell et al. 2005, Jogee et al. 2009).

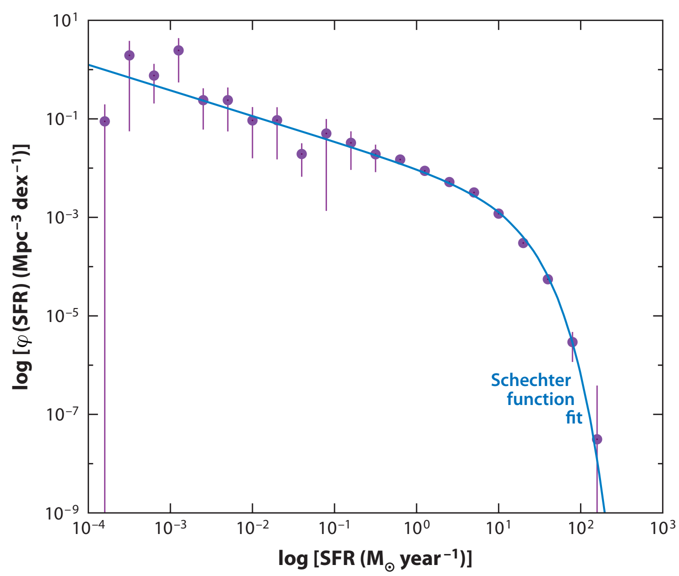

Figure 10

Volume-corrected star-formation-rate (SFR) distribution function for disk and irregular galaxies in the local Universe, as derived from a combination of large flux-limited ultraviolet and infrared catalogs and a multiwavelength survey of the local 11-Mpc volume. Vertical lines indicate uncertainties due to finite sampling; these are especially important for low SFRs where the statistics are dominated by dwarf galaxies that can be observed only over small volumes. Statistics on gas-poor (elliptical, dwarf spheroidal) galaxies are not included in this study. The blue line shows a maximum-likelihood Schechter function fit, as described in the text. Figure is original, but similar to one in Bothwell et al. (2011).

6. STAR-FORMATION RELATIONS

The immense dispersion in SFR properties seen in **Figure 9** collapses to a remarkably tight scaling law when the SFR surface densities (SFR) are plotted against mean gas surface densities ($SIGMA_{gas}$) (Kennicutt 1998b). This emergent order reflects the fact that gas is the input driver for star formation. The concept of a power-law relation between SFR density and gas density dates to Schmidt (1959, 1963), and relations of this kind are commonly referred to as Schmidt laws. On physical grounds, we may expect the most fundamental relation to be between the volume densities of star formation and gas, but because most observations of external galaxies can measure only surface densities integrated along the line of sight, the most commonly used relation, often called a Kennicutt-Schmidt (KS) law, is in terms of surface densities:

$$\Sigma_{\rm SFR} = A\,\Sigma_{\rm gas}^{N}.$$

The precise form of this relation depends on assumptions about how $_{\rm gas}$ is derived from the observations (Section 2.4), but a strong correlation is clearly present.

The slope of the integrated Schmidt law is nonlinear, with $N \simeq$ 1.4–1.5 (Kennicutt 1998b) when a constant X(CO) factor is applied. This uncertainty range does not include all possible systematic errors, arising, for example, from changes in X(CO) or the IMF with increasing surface density or SFR. Major systematic changes in either of these could easily change the derived value of N by as much as 0.2–0.3. For example, if X(CO) were five times lower in the dense starburst galaxies (Section 2.4), the slope of the overall Schmidt law would increase from 1.4–1.5 to 1.7–1.9 (Narayanan et al. 2011).

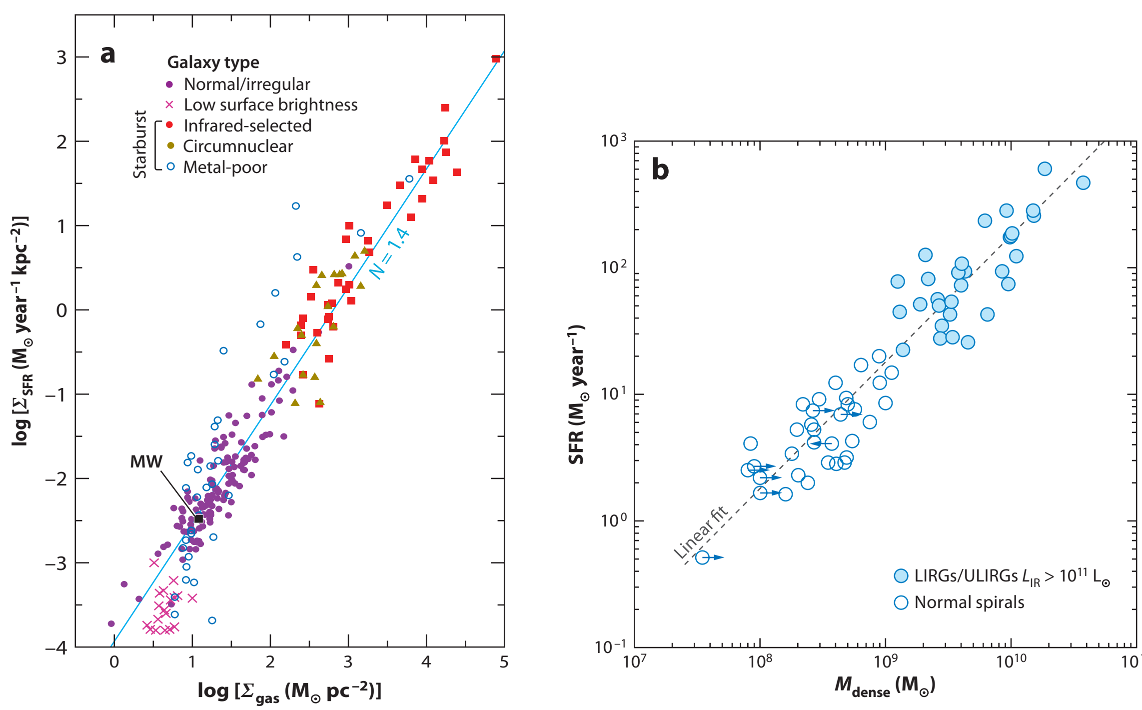

Figure 11

(*a*) Relationship between the disk-averaged surface densities of star formation and gas (atomic and molecular) for different classes of star-forming galaxies. Each point represents an individual galaxy, with the SFRs and gas masses normalized to the radius of the main star-forming disk. Colors are used similarly as in **Figure 9**: Purple points represent normal spiral and irregular galaxies, red points infrared-selected starburst galaxies [mostly luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs, respectively)], and dark yellow points denote circumnuclear starbursts with star-formation rates (SFRs) measured from Paα measurements. The Milky Way (*black square*) fits well on the main trend seen for other nearby normal galaxies. Magenta crosses represent nearby low-surface-brightness galaxies, as described in the text. Open blue circles denote low-mass irregular and starburst galaxies with estimated metal (oxygen) abundances less than 0.3 $Z_\odot$, indicating a systematic deviation from the main relation. For this plot, a constant X(CO) factor was applied to all galaxies. The light blue line shows a fiducial relation with slope N = 1.4 (not intended as a fit to these data). The sample of galaxies has been enlarged from that studied in Kennicutt (1998b), with many improved measurements as described in the text. (*b*) Corresponding relation between the total (absolute) SFR and the mass of dense molecular gas as traced in HCN. The dashed gray line is a linear fit, which contrasts with the nonlinear fit in panel *a*. Figure adapted from Gao & Solomon (2004). Reproduced by permission of the AAS.

Finally, a number of workers have explored the scaling between SFR surface density and a combination of gas and stellar surface densities. For example, Dopita (1985) and Dopita & Ryder (1994) proposed a scaling between the SFR density and the product of gaseous and stellar surface densities; the latter scales with the disk hydrostatic pressure and, hence, bears some relation to the picture provided by Blitz & Rosolowsky (2006). More recently Shi et al. (2011) showed that the scatter in the star-formation law is minimized with a relation of the form $\propto$ $^{0.5}$.

$_{\mathrm{SFR}}$ $_{\mathrm{gas}}$ $_{*}$ Determining which of these different formulations of the star-formation law is physical and which are mere consequences of a more fundamental relation is difficult from observations alone. Some of the degeneracies between these various relations can be understood if most gas disks lie near the limit of gravitational stability ($Q \sim 1$) (Kennicutt 1989), and the critical column densities for the formation of cold gas phase, molecule formation, and gravitational instability lie close to each other (e.g., Elmegreen & Parravano 1994, Schaye 2004). In such conditions, it can be especially difficult to identify which physical process is most important from observations.

Galaxy Formation

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10. – The two modes of star formation

10˙1. The SFR main sequence and starburst galaxies. – Alongside with the two modes of gas accretion, two main modes of star formation are known to control the growth of galaxies: a relatively steady rate in disk galaxies, although intermittent in dwarfs, which defines the main star formation rate-stellar mass sequence, and a starburst mode in outliers of such a sequence, fig. 28. Such starburst galaxies, which are generally interpreted as driven by mergers, are relatively rare at $z \sim 2$ and have considerably higher SFRs. In the aim of establishing the relative importance of these two modes, reference [132] analyzed several sample of galaxies. They conclude that merger-driven starbursts play a minor role for the formation of stars in galaxies, whereas they may represent a critical phase towards the quenching of star formation and morphological transformation in galaxies.

Morphologies confirm this picture for luminous star-forming galaxies, both locally and at $z \sim 1$ [133]. Most galaxies with IR luminosities above 3x 10^{11}L are found to show merger-induced morphological disturbances and the fraction of such deviations from normality increases systematically with distance above the galaxy main sequence.

Star-forming galaxies at $z \sim 2$ often contain a small number of extremely massive star-forming clumps. Resolution using adaptive optics reveals that the clumps are un- dergoing extreme rates of star formation [134]. Such rates may be difficult to achieve with purely gravitational triggering as found in local star-forming galaxies. Simulations suggest that such clumps, presumably formed by violent disk gravitational instabilities, may generate outflows but survive for $\gtrsim 10^8$yr, long enough to fall into the central regions and contribute to bulge formation and black hole growth [135]. (COMPARE INSET WITH KENNICUTT & EVANS FIG. 8)

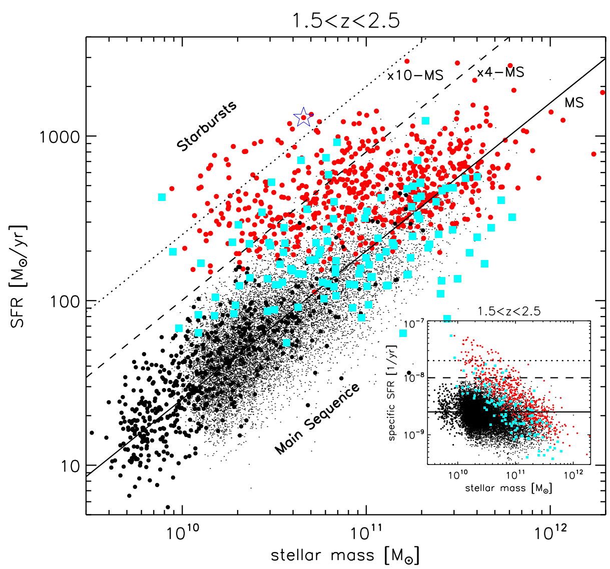

Fig. 28. – Star formation rate vs stellar mass relation at $1.5 < z < 2.5$, for different samples of galaxies (various symbols). The solid black line indicates the Main Sequence of star forming galaxies, and a population of starbursts is evident in the top left panel. In the inset, the same relation is shown but as a function of specific SFR. Figure from [132].

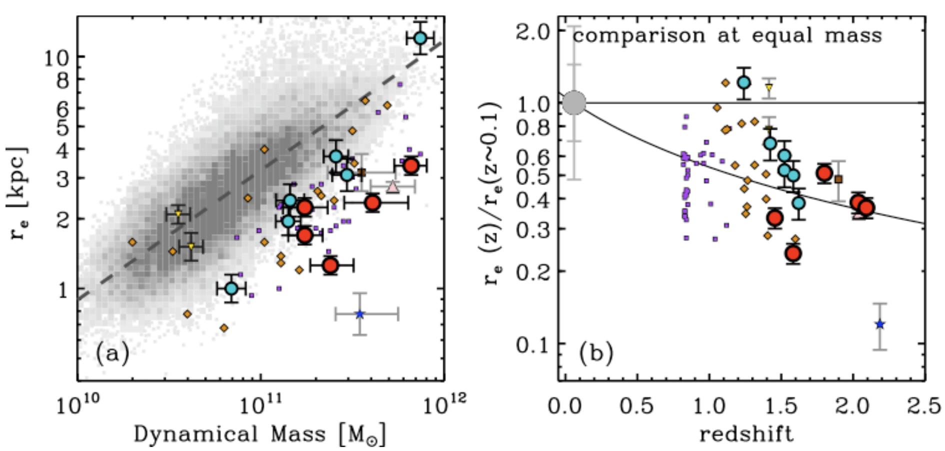

Fig. 29. – Evolution of the effective radius of passive galaxies with redshift. Left panel, size vs. dynamical mass: $z \sim 2$ galaxies (red circles) are smaller by a factor 3 compared to low-redshift galaxies. Right panel, evolution of the effective radius at fixed dynamical mass vs. redshift. The solid line is the best-fit $r_e \approx (1 + z)^{-0.97\pm0.10}$. Figure from [136].

10˙2. Evolution of early-type galaxies (ETG). – Isolated, early-type galaxies such as ellipticals and S0s, usually evolve in a passive way, with few signs of any on-going star formation. Such passive galaxies, however, are observed to grow in size. The mass- size relation of ETGs has been largely studied to probe their mass assembly history. The general picture is that the inner parts of ETGs form in situ after gas accretion and gas-rich mergers at $z > 2$, while the outer parts form via minor mergers at $z < 2$. Reference [136] used stellar kinematics measurements to investigate the growth of massive, quiescent galaxies from $z \sim 2$ to today, fig.29. They found an inside-out growth of quiescent galaxies, consistent with expectations from minor mergers.

Moreover, passive galaxies have been found to be larger in clusters than in the field. [137] studied the mass-size relation of quiescent massive ETGs living in massive clusters at $0.8 < z < 1.5$, as compared to those living in the field at the same epoch. The authors find that ETGs in clusters are ~ 30 50% larger than galaxies with the same stellar mass residing in the field. They parametrize the size using the mass-normalized size, = R /$M^{0.57}$, fig.30. The size difference seems to be essentially driven by the galaxies residing in the cluster cores. They conclude that part of the size evolution is due to mergers: the observed differences between cluster and field galaxies could be due to higher merger rates in clusters at higher redshift.

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Cole’s paper!

Secular Evolution and the Formation of Pseudobulges in Disk Galaxies

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The Universe is in transition. At early times, galactic evolution was dominated by hierarchical clustering and merging, processes that are violent and rapid. In the far future, evolution will mostly be secular—the slow rearrangement of energy and mass that results from interactions involving collective phenomena such as bars, oval disks, spiral structure, and triaxial dark halos. Both processes are important now. This review discusses internal secular evolution…

In the distant future, internal secular processes will become dominant. These are defined to be slow processes, i.e., ones that have timescales much longer than $t_{\rm dyn}$. To be interesting, they must operate over long times. Some secular processes, such as disk heating via stellar enounters with molecular clouds, are well known (Spitzer & Schwarzschild 1951, 1953). But star-star relaxation is too slow to be important almost everywhere in almost every galaxy. Therefore, relevant secular processes generally involve the interactions of individual stars or gas clouds with collective phenomena such as bars, oval distortions, spiral structure, and triaxial dark matter halos. Also important are the interactions of these collective phenomena with each other. Given that hierarchical clustering continues today, has there been time for slow processes to be important? For secular evolution to have a significant effect, a galaxy must be free of major mergers for a long time, because merger violence erases the signature of secular processes. Hierarchical clustering results in so many mergers that one might guess that secular processes are relatively unimportant. A clue that this is frequently not the case is provided by galaxies with superthin—and fragile—disks but apparently no bulges (e.g., Matthews, Gallagher & van Driel 1999b; Freeman 2000; van der Kruit et al. 2001). They show that many galaxies have suffered no major merger violence since the onset of star formation in the disk (To´th & Ostriker 1992). Therefore there has been time for secular evolution to be important in at least some galaxies. Given that mergers make bulges and ellipticals, these tend to be late-type galaxies. Actually, because the latest-type galaxies are (pseudo)bulgeless, secular evolution is likely to be most important in intermediate- late-type galaxies, i.e., Sbcs. But even some S0 and Sa galaxies contain pseudo- bulges. Secular processes have received less attention than galaxy mergers.

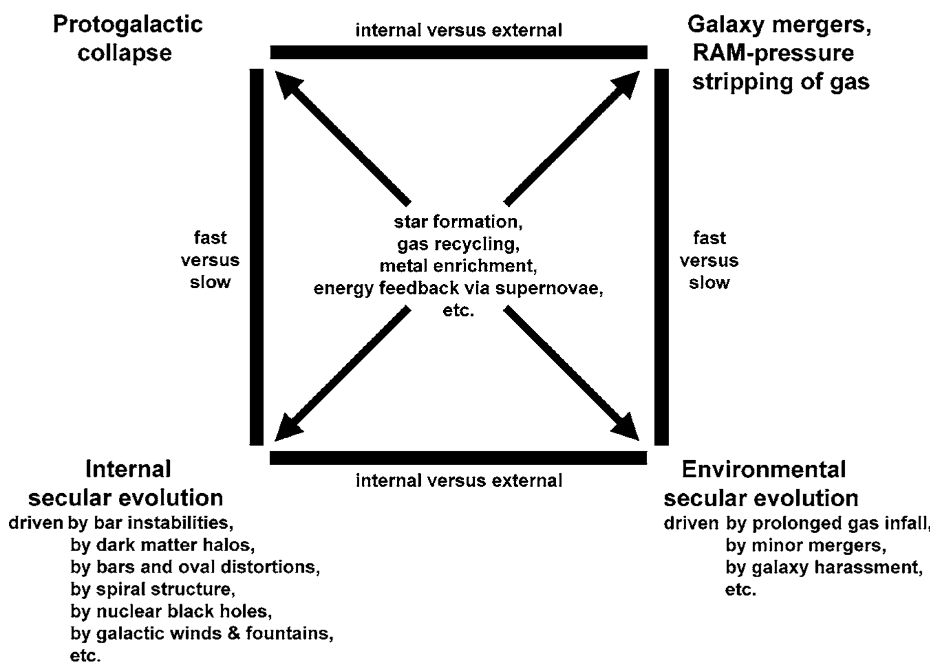

Figure 1 Morphological box (Zwicky 1957) of processes of galactic evolution updated from Kormendy (1982a). Processes are divided vertically into fast (*top*) and slow (*bottom*). Fast evolution happens on a free-fall ("dynamical") timescale, $t_{\rm dyn} \sim (G\rho)^{-1/2}$, where ρ is the density of the object produced and G is the gravitational constant. Slow means many galaxy rotation periods. Processes are divided horizontally into ones that happen purely internally in one galaxy (*left*) and ones that are driven by environmental effects such as galaxy interactions (*right*). The processes at center are aspects of all types of galaxy evolution. This paper is about the internal and slow processes at lower left.